IV. Accumulator

A. Function

The purpose of the Accumulator, as its name implies, is to accumulate antiprotons. This is accomplished by momentum stacking successive pulses of antiprotons from the Debuncher over several hours or days. Both RF and stochastic cooling systems are used in the momentum stacking process. The RF decelerates the recently injected pulses of antiprotons from the injection energy to the edge of the stack tail. The stack tail momentum cooling system sweeps the beam deposited by the RF away from the edge of the tail and decelerates it towards the dense portion of the stack, known as the core. Additional cooling systems keep the pbars in the core at the desired momentum and minimize the transverse beam size.

What follows is a chronological sequence of events that takes place in the Accumulator:

1) Unbunched antiprotons are extracted from the Debuncher, transferred down the Debuncher to Accumulator (D/A) line, and injected into the Accumulator with a kinetic energy 8 GeV. The beam is transferred in the horizontal plane by means of a kicker and pulsed magnetic septum combination in each machine (in order: D:EKIK, D:ESEPV, A:ISEP2V, A:ISEP1V and A:IKIK). Extraction in the Debuncher occurs just before another antiproton pulse arrives from the target.

2) The Accumulator injection kicker puts the injected antiproton pulse onto the injection closed orbit which is roughly 80mm to the outside of the central orbit. The kicker is located in a high dispersion region so the higher energy injected beam is displaced to the outside of the Accumulator. This kicker is unique in that there is a shutter which moves into the aperture between the injection orbit and the circulating stacktail and stack. The shutter is in this position only when the kicker fires. The shutter's purpose is to shield the circulating antiprotons already in the Accumulator from fringe fields created when the kicker fires. Figure 4.1 diagrams a spectrum analyzer display of the Accumulator longitudinal beam distribution as seen on CATV pbar channel 29 and shows the

relative location of the shutters in revolution frequency (which relates to the horizontal position in a dispersive region).

3) After the injected pbars have been kicked onto the injection closed orbit, the shutter is opened and a 53 MHz RF system known as ARF-1 captures the beam in 84 bunches. ARF-1 then decelerates the beam by approximately 60 MeV to the edge of the stack tail, beyond the space occupied by the kicker shutter. The RF is adiabatically (very slowly) turned off as the edge of the tail is

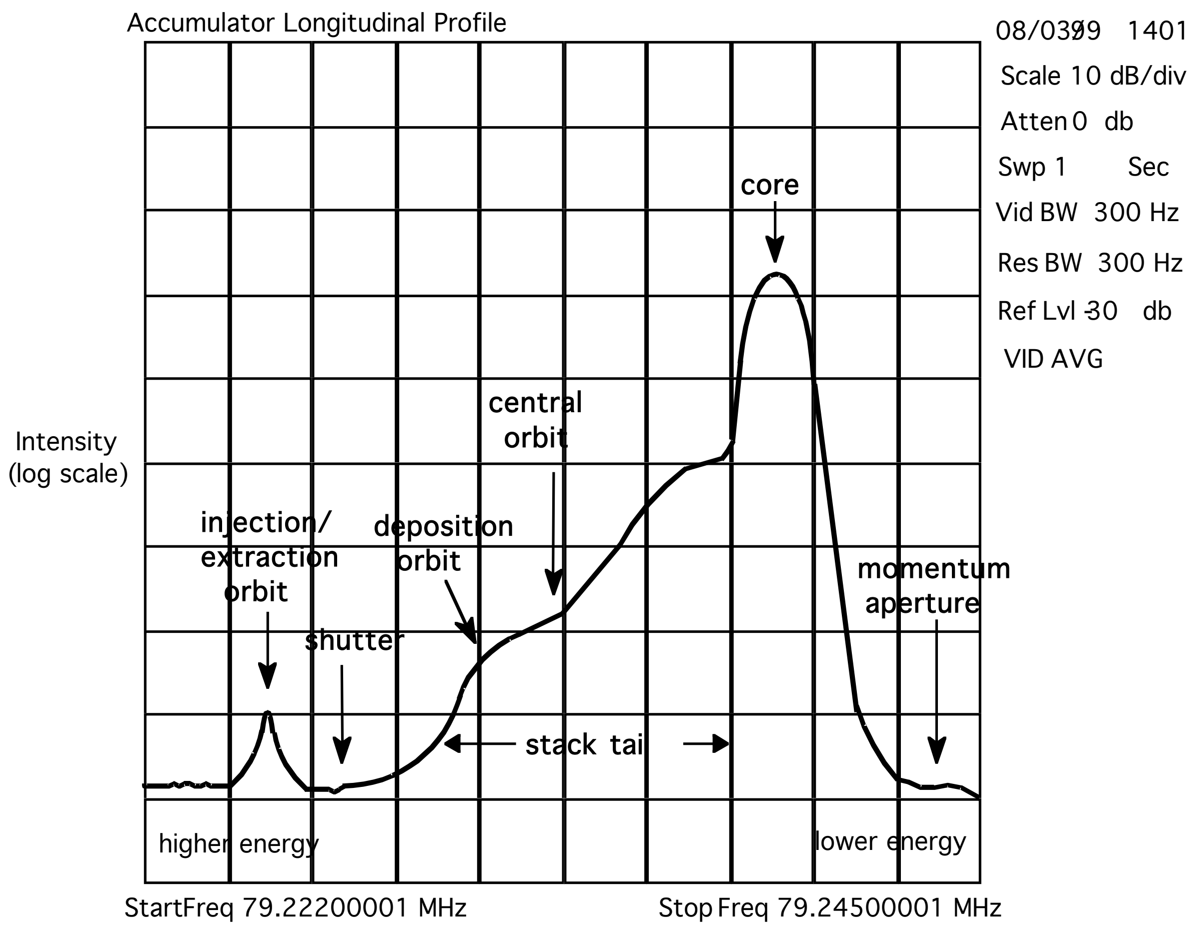

Figure 4.1 Accumulator stack profile

approached and the now unbunched pbars are deposited into the stack tail.

4) The stack tail momentum cooling system now acts on the pbars. This system decelerates the beam towards the stack core which is approximately -150 MeV from the injection orbit (or ~63 mm to the inside of the Accumulator central orbit in a high dispersion region).

5) After approximately 30 minutes, the antiprotons in the stack tail have been decelerated into the domain of the core cooling systems. Six stochastic cooling systems act on beam in the core during stacking. The 2-4 GHz and 4-8 GHz core momentum systems control the momentum spread and keeps the pbars from hitting the low momentum aperture. The 2-4 GHz and 4-8 GHz core horizontal and vertical betatron cooling systems keep the transverse emittances minimized.

6) This process continues for hours or days with the stack growing in size until the desired Accumulator intensity is reached or the Tevatron needs to be refilled.

7) When a transfer of pbars to the Main Injector is desired, an RF system known as ARF-4 is utilized. ARF-4 has a harmonic number of h=4 and is energized at a very low amplitude at a frequency corresponding to that of the revolution frequency of beam in the core. The RF voltage is slowly increased and a portion of the beam in the core is captured into four buckets and is slowly moved through the stack beyond the space occupied by the shutter, and onto the extraction orbit (at the same frequency as the injection orbit).

8) Once the unstacked bunch is on the extraction orbit, the ARF-4 voltage is increased. The additional voltage acts to shrink each bunch longitudinally, giving them the same distribution in time as 10-12 Main Injector 53 MHz bunches.

9) Just before the extraction kicker is fired, ARF-1, is energized and the antiprotons destined for the Main Injector are rebunched into 11 or so bunches suitable for capture by MIRF.

10) The extraction kicker shutter closes, then the kicker is fired. Like its injection counterpart, the extraction kicker has a shutter to shield the remaining stack from fringe fields. The deflection imparted by the kicker provides sufficient horizontal displacement to place the kicked beam in the field region of a Lambertson magnet in straight section 30 which bends the beam up out of the Accumulator and into the AP3 line.

B. Lattice

The Accumulator "ring" actually resembles a triangle with flattened corners. The lattice has been designed with the following constraints in mind.

- The Accumulator must be capable of storing an antiproton beam over many hours.
- There must be several long straight sections of lengths up to 16 m with small transverse beam sizes to accommodate stochastic cooling pickups and kickers.
- Some of these sections must have low dispersion, others with dispersion of about 9 m (high dispersion).
- Betatron cooling pick-ups and kickers must be an odd multiple of $\pi/2$ apart in betatron phase (i.e. the number of betatron oscillations) and far enough apart physically so that a chord drawn across the ring will be significantly shorter than the arc. Cooling pickup signals must arrive at the kickers on the same turn in time to act on the particles that created the signal.

The end result is that the Accumulator has an unconventional triangular shape that includes 6 straight sections with alternately low and high dispersion. This shape was considered most efficient as compared to other designs, which were up to 10-sided.

The reader may wonder what the need is for high and low dispersion sections or what the difference is. The dispersion function (often written η_x or η_y) describes the contribution to the transverse size of a particle beam as a result of its momentum spread. Dispersion is caused in large part by bending magnets, different momenta particles are bent at different angles as a function of the momentum. In a low dispersion area, the beam size is almost entirely defined by the β function and the normalized emittance of the beam. In a high dispersion region, the beam size is defined by the β function and normalized emittance as well as the dispersion function. In the case of the Accumulator, the horizontal β function is largest in the high dispersion regions in addition to the large horizontal dispersion function. As a result, the beam size is very small in the low dispersion areas and very wide horizontally in the high dispersion areas (there is very little vertical dispersion due to the fact that there are only small vertical trim dipoles in the Accumulator). Normalized emittance, often written as ε_n, describes the transverse size of the beam independent of the beam energy, β function and dispersion function.

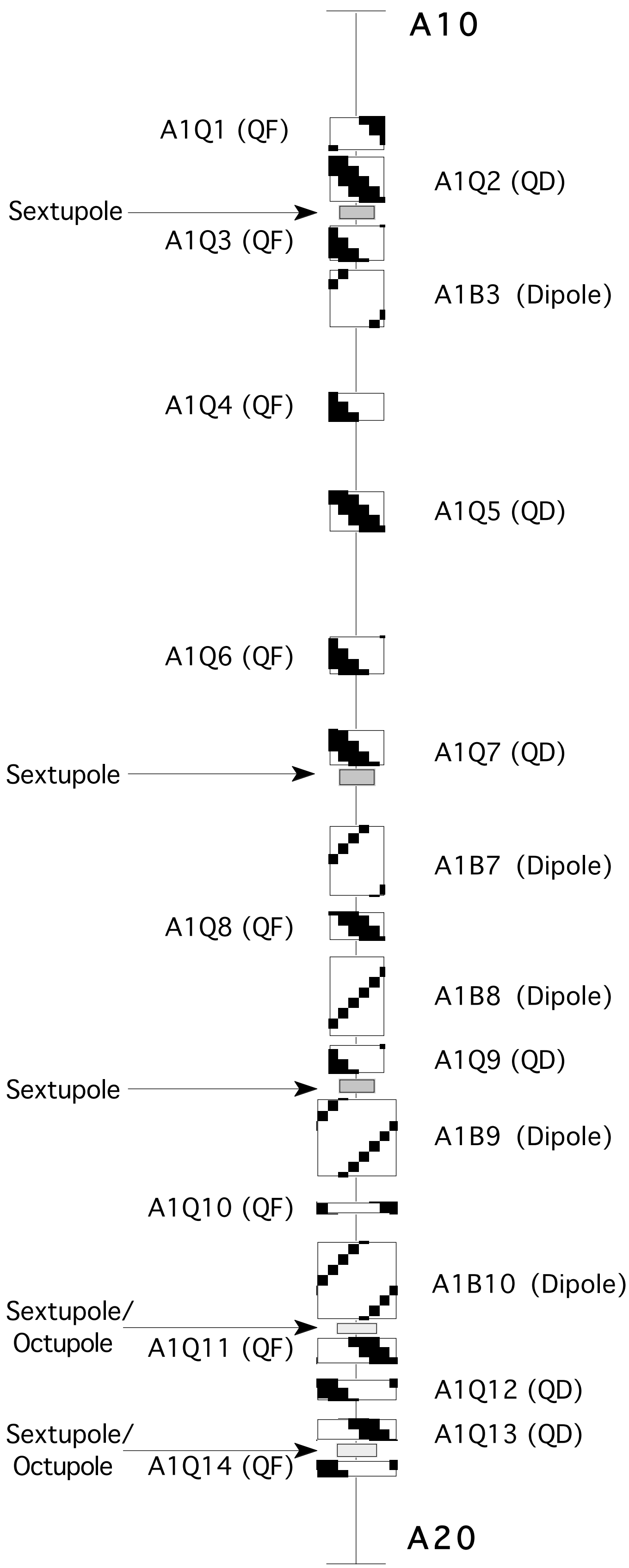

Figure 4.2 Accumulator lattice

Low dispersion regions can be used by cooling systems to sense a beam position error due to transverse oscillations. In a similar vein, position errors in a high dispersion section can in large part be attributed to off-momentum beam. In the case of the Accumulator, betatron cooling system pickups are best placed in low dispersion straights while momentum cooling pickups are found in one of the high dispersion straight sections.

The lattice of the Accumulator, shown in figure 4.2, is much different from the Debuncher. There are special arrangements of quadrupoles approaching the straight sections in order to achieve the desired dispersion. Like the Debuncher, the Accumulator has mirror symmetry about the straight sections. The magnet numbering scheme increases as one travels in the pbar direction in the odd-numbered sectors, and decreases in the even sectors. Like the Debuncher, the Accumulator straight sections are full of specialized devices. A10 contains core betatron cooling pickup tanks, Schottky and other diagnostic pickups, damper pickups and kickers as well as the beam current transformer for measuring the circulating beam intensity. The injection and extraction kickers are found in straight section 20, as are the pickup arrays for the 4-8 GHz core momentum cooling system. In A30 reside the extraction Lambertson magnetic septum, the stack tail momentum, 2-4 GHz core momentum, and core betatron cooling kickers. Section 40 contains a beam scraper used for measuring Δp/p and a set of flying wires for making high dispersion measurements of the beam size. A50 contains transverse scrapers as well as space for detectors for E835 or other experiments. The various Accumulator RF cavities are also found in A50. Just upstream of the actual straight section is the kicker tank for the 4-8 GHz core momentum system and a set of flying wires for making low dispersion measurements of the beam size. Straight section 60 contains all of the stochastic cooling pickups for the stack tail momentum systems and the 2-4 GHz core Δp cooling pickups.

C. Power supplies

The main dipoles and quadrupoles in the Accumulator are powered by five different power supplies, A:QT is located in AP10 and the others are located at AP50. All of the dipoles are powered in series by A:IB, a large 12-phase PEI supply. Like D:IB, it has a separate 13.8 kV transformer outside of the building. The setting of the A:IB power supply is not changed arbitrarily. The nominal bend field is closely coupled to both the Debuncher and the Main Injector. The Debuncher main dipole field is set to provide pbars at the correct injection frequency of the Accumulator. The extraction revolution frequency of the Accumulator must be matched to the Main Injector injection energy. The Accumulator bend field is only changed after checking for an energy mismatch between the Main Injector and the Accumulator.

The 'large' quadrupoles, the ones found on either side of the high dispersion straight sections numbered ten through fourteen, are all powered by A:LQ. Similarly, quadrupoles adjacent to the low dispersion sections, the first through third quads in a sector, as well as the six location quads, are connected to the A:QT bus. Outside of the straight sections one finds alternately focusing and defocusing quadrupoles. With the exception of the six location, these are all powered by a single supply, A:QDF. Current is delivered to each type of quad after passing through one of two shunts on the output of this supply. A:QSF1 shunts current from the focusing quads, A:QSD is the shunt for the defocusing quadrupoles. The current delivered to the focusing and defocusing quadrupoles differs by a few percent at most. The Accumulator tunes are varied by changing all of the above quadrupole devices simultaneously in a predetermined ratio (mult).

As a cost-cutting measure, the Accumulator magnets were built to provide fields for 8 GeV particles, hence run close to or at magnetic saturation at 8 GeV. For this reason, changes to the bend and quad buses should not be made lightly as hysteresis effects may be significant. To provide for reproducible tunes and orbits, the major supplies are "cycled" or ramped from nominal to zero current three times following any period when the supplies have been turned off (like for an access) or their values changed significantly (such as during deceleration for E835).

In addition to dipoles and quadrupoles, higher order correction element strings can be found in the Accumulator. Five sextupole supplies known as A:SEX3, A:SEX7, A:SEX9, A:SEX10, and A:SEX12 power sextupole magnets located adjacent to the third, seventh, ninth, tenth and twelfth quadrupoles in

Table 4.1 Accumulator RF systems

each cell. Octupoles are found near the tenth and twelfth quads and are powered respectively by A:OCT10 and A:OCT12. In fact, the sextupole and octupole magnets in the '10' and '12' locations are wound on the same frame, the fields being formed by the shape and location of the windings rather than the number of poles.

Three other supplies deserve mention: decoupling of the horizontal and vertical tunes is possible by means of two skew quadrupole magnets powered by A:SQ100 and A:SQ607. Both supplies have reversing switches, which make it possible to reverse the polarity of either magnet. Finally, there is the extraction Lambertson magnet powered by D:ELAM. This supply is kept on during normal Collider operation despite the fact that it is needed only during reverse injection of protons and transfers of antiprotons. The higher order fields produced by the Lambertson are sufficiently strong in the 'field-free region' so as to cause noticeable tune and coupling differences when on versus off.

Fine control of the Accumulator orbit is possible by means of a combination of trim dipoles, dipole shunts and motorized dipoles. Each main dipole in the Accumulator has a shunt, permitting individual control of the current passing through each, providing some horizontal orbit control. The shunts can be used in combination with other shunts or horizontal trims to produce local bumps. Due to space limitations, the AxB8 and AxB10 dipole magnets have stepping motors on their magnet stands allowing them to be rolled slightly. Rolling the dipole imparts a vertical deflection on the beam and can be used in place of a vertical trim magnet. Both horizontal and vertical trims are located near beam transfer points. Vertical trims are also located in the arcs.

System	Freq.	Harm.	Peak Voltage	Amplitude	Frequency
ARF-1	52.8 MHz	h=84	80 kV	DAC (A:R1LLAM) 164 card (A:R164AM)	DAC (A:R1LLFR) 164 card (A:R164FR)
ARF-2	1.26 MHz	h=2	200 V	DAC (A:R2LLAM) 164 card (A:R264AM)	DDS (A:R2FSET) 468 card (A:R268FF)
ARF-3	1.26 MHz	h=2	6,000 V	DAC (A:R3LLAM) 164 card (A:R364AM)	DDS (A:R2FSET) 468 card (A:R268FF)
ARF-4	2.5 MHz	h=4	1,000 V	DAC (A:R4LLAM) 466 card (A:R466A)	DDS (A:R2FSET) 468 card (A:R268FF)

D. RF systems

1. ARF-1

The Accumulator has four RF systems, ARF-1, ARF-2, ARF-3 and ARF-4. Table 4.1 summarizes attributes of the various Accumulator RF systems. ARF-1, the 52.8 MHz (h=84) system, serves a dual purpose, used both for stacking and transfers to the Main Injector. Figure 4.3 shows the voltage and frequency waveforms used during stacking. When stacking, ARF-1 is used to move beam from the injection orbit across the kicker shutter aperture to the high-energy edge of the stack tail (deposition orbit). This process takes about 430 milliseconds. As beam from the Debuncher enters the Accumulator, it is a nearly continuous stream with a small momentum spread and no bunch structure. In order to efficiently capture the beam, ARF-1 bunches the beam adiabatically. The phase is then shifted ~0.6 degree and the frequency increased by ~10 kHz to decelerate the beam to the edge of the stack tail.

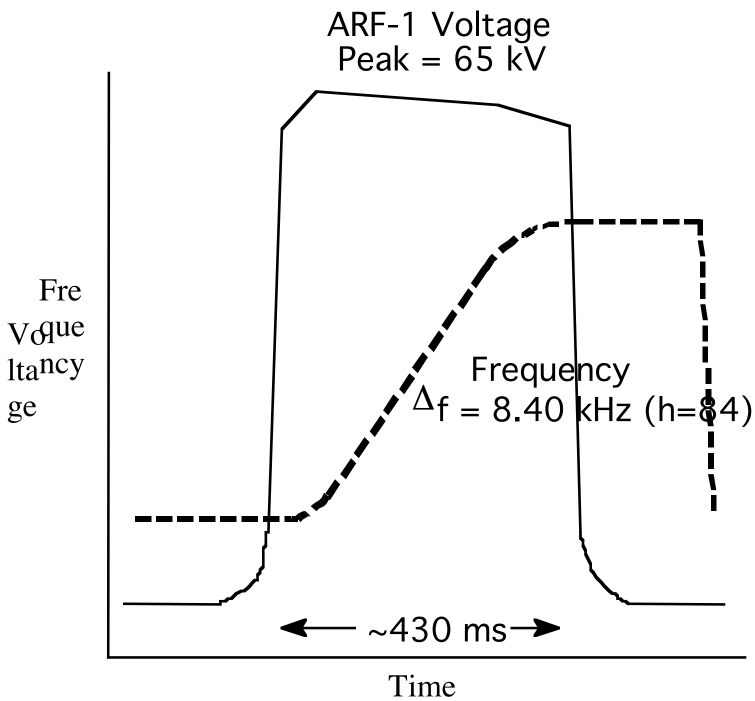

Figure 4.3 ARF-1 Waveforms for Stacking

Next, the beam is debunched by adiabatically reducing the RF voltage. The antiprotons experience an energy reduction of 0.7%.

Transfers of antiprotons back to the Main Injector are accomplished by means of a bucket to bucket (synchronous) transfer (pbars could be adiabatically bunched in the Main Injector, but poor 8-GeV lifetime made the option less desirable). For synchronous transfer, the bunch structure of the extracted pbars must be compatible with the Main Injector RF bucket structure. ARF-1 was designed as a 52.8 MHz h=84 machine to serve this purpose. After beam arrives on the extraction orbit, the ARF-1 voltage is raised in 450 milliseconds to 65 kV to impart the 52.8 MHz structure on the beam.

Antiprotons are extracted from the core by ARF-4 as four h=4 bunches, as will be detailed below. ARF-1 is turned on shortly before extraction and gives the antiprotons a 52.8 MHz bunch structure. The net result is four sets of approximately eleven 52.8 MHz bunches being transferred to the Main Injector. Eleven bunches is about the largest number of bunches that the Main Injector can coalesce efficiently. A larger increase in ARF-4 voltage prior to extraction would further narrow the bunches (fewer 52.8 MHz bunches would be created) but at the cost of a larger dp/p for the individual 52.8 MHz bunches. Figure 4.4 shows the voltage and frequency waveforms used to bunch the unstacked beam just prior to transfer. To facilitate a synchronous transfer, ARF-1 is phase-locked to Main Injector/Recycler low level RF.

The amplitude reference for ARF-1 can be switched to either a DAC (A:R1LLAM) or a 164 card (A:R164AM). The frequency inputs also are provided by both a DAC (A:R1LLFR) or a 164 card (A:R164FR). The 164 card is phase locked to the Direct Digital Synthesizer (DDS) used by ARF-4 during unstacking. A Sciteq frequency oscillator can also be switched in but is only used during studies.

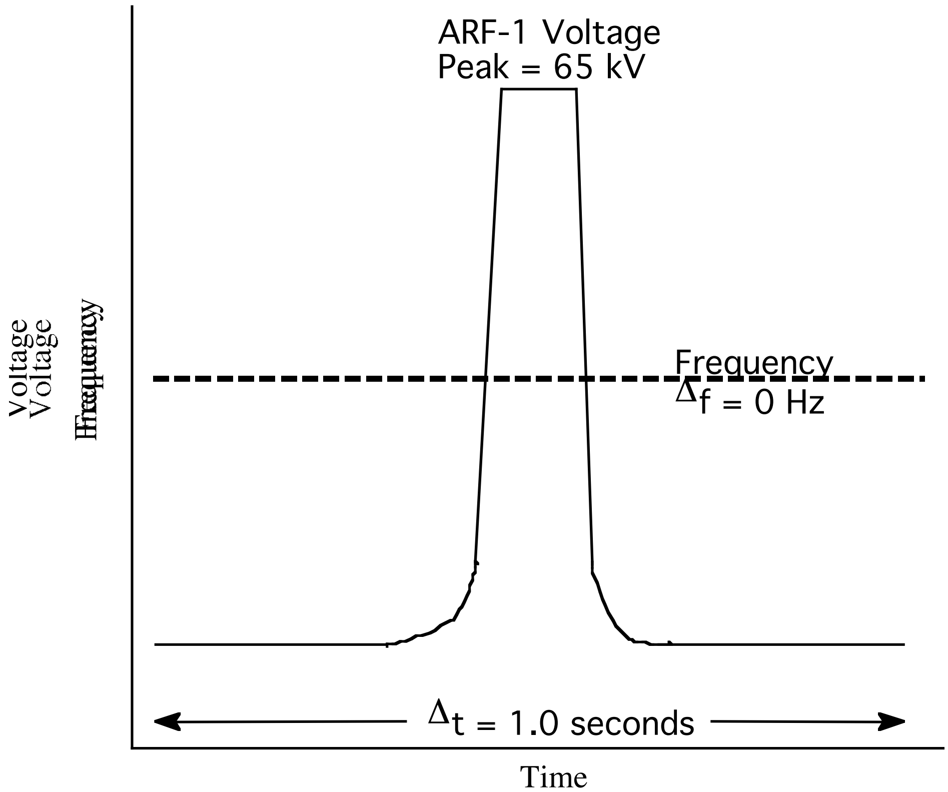

Figure 4.4 ARF-1 Waveforms for Antiproton transfers to the Main Injector

2. ARF-2

ARF-2 was originally used to unstack beam from the core during collider operation. The shift from 6 proton on 6 antiproton bunch operation to 36 on 36 operation required a more timely means of transferring the antiprotons. By removing the pbar bunches four at a time with ARF-4, only 9 unstacking sequences are required instead of 36. ARF-2 is an h=2, 1.26 MHz system that has one of the two buckets suppressed in a manner similar to DRF-2, but not using a barrier bucket (see figure 4.5). This is accomplished by a module, which suppresses every other RF cycle and sends the resultant wave to the high level.

Amplitude control of ARF-2 can be switched to either a DAC (A:R2LLAM) or a 164 card (A:R264AM). The frequency inputs are provided by a DDS that can be set to a DC level (A:R2FSET) or driven by a 468 card (A:R268FF). Note that A:R2FSET and A:R268FF are simultaneously used for the ARF-2,3 and 4 reference.

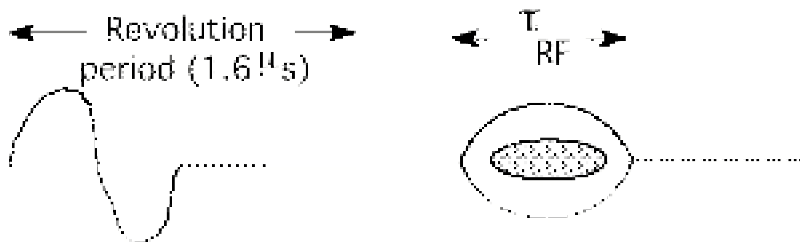

Figure 4.5 ARF-2 structure

The primary function for ARF-2 now is for "stabilizing RF" to minimize the number of trapped positive ions in the Accumulator. Approximately 10-20V of RF is applied at the core revolution frequency to weakly bunch the beam. This bunching of the beam acts to dislodge trapped positive ions from their potential wells.

3. ARF-3

ARF-3 was used for many years to narrow bunches on the extraction orbit. With the advent of ARF-4, ARF-3 is no longer used in the extraction process. ARF-3 operates at 1.26 MHz and h=2, it does not have a suppressed bucket like ARF-2 (see figure 4.6).

Now the primary use for ARF-3 is for decelerating stacks for E835. As will be explained in more detail in a later chapter, E835 studies charmonium states and needs to have a pbar beam at the resonance energies of these states. This requires the stack to be decelerated, accomplished by bunching the antiprotons at 8 GeV and decreasing the RF frequency synchronously with the decreasing bend field until the desired energy is reached.

The low-level amplitude input to ARF-3 comes from either a DAC (A:R3LLAM) or a 164 card (A:R364AM). As with ARF-2, the frequency inputs are provided by a DDS that can be set to a DC level (A:R2FSET) or driven by a 468 card (A:R268FF).

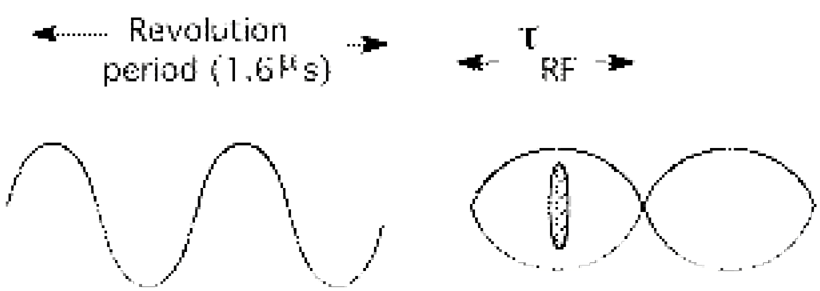

Figure 4.6 ARF-3 structure

For E835

operation, the amplitude is controlled by the DAC and frequency information is sourced by a 10 MHz digital frequency synthesizer, known as a SCITEQ. The front-end computer has special code to control the waveforms of these devices during deceleration.

3. ARF-4

The entire stack is never extracted when antiprotons are transferred to the Main Injector. Rather, a portion of the densest part of the stack is adiabatically captured and accelerated to the extraction orbit. When removing antiprotons from the core, the ARF-4 voltage is slowly increased to capture a portion of the core as defined by the bucket size. The synchronous phase angle is then changed until the bunches are accelerated out of the core to the extraction orbit. The phase angle returns to zero once beam reaches the extraction orbit. The entire process of unstacking pbars takes approximately 40 seconds.

ARF-4 is a 2.52 MHz h=4 system that was created to allow the transfer of 4 groups of 11 52.8 MHz bunches at a time. Therefore, a typical transfer involves 9 extractions, each one comprised of 4 individual sets of antiproton

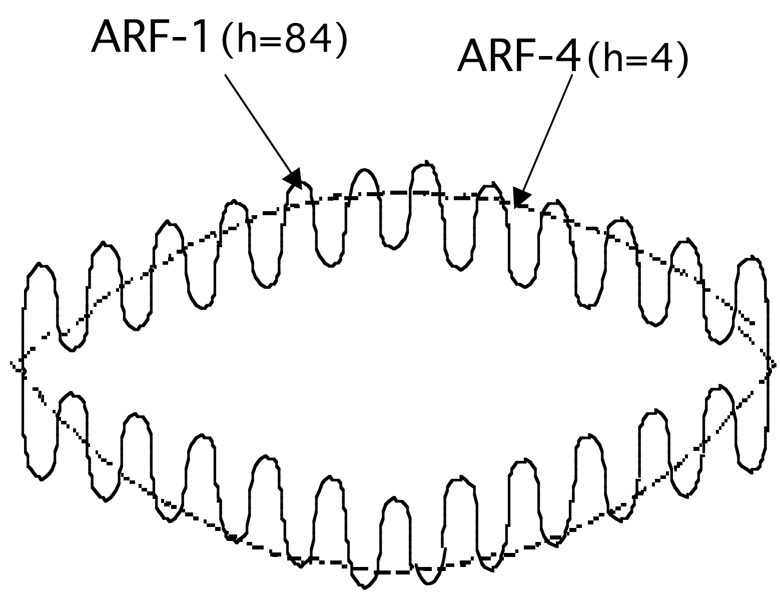

Figure 4.7 Accumulator bunch structure with both ARF-1 and ARF-4 on

bunches. ARF-2 and ARF-3 are not involved in the extraction process at all, the ARF-4 voltage is simply turned up to narrow the h=4 bunches. ARF-1 is turned on just prior to extraction to create 11 52.8 MHz bunches within each of the four h=4 bunches. Figure 4.7 shows the bunch structure on each of the h=4 bunches while Figure 4.8 shows a typical ARF-4 waveform during unstacking.

The low-level amplitude input to ARF-4 comes from either a DAC (A:R4LLAM) or a 466 card (A:R466A). As with ARF-2 and 3, the frequency

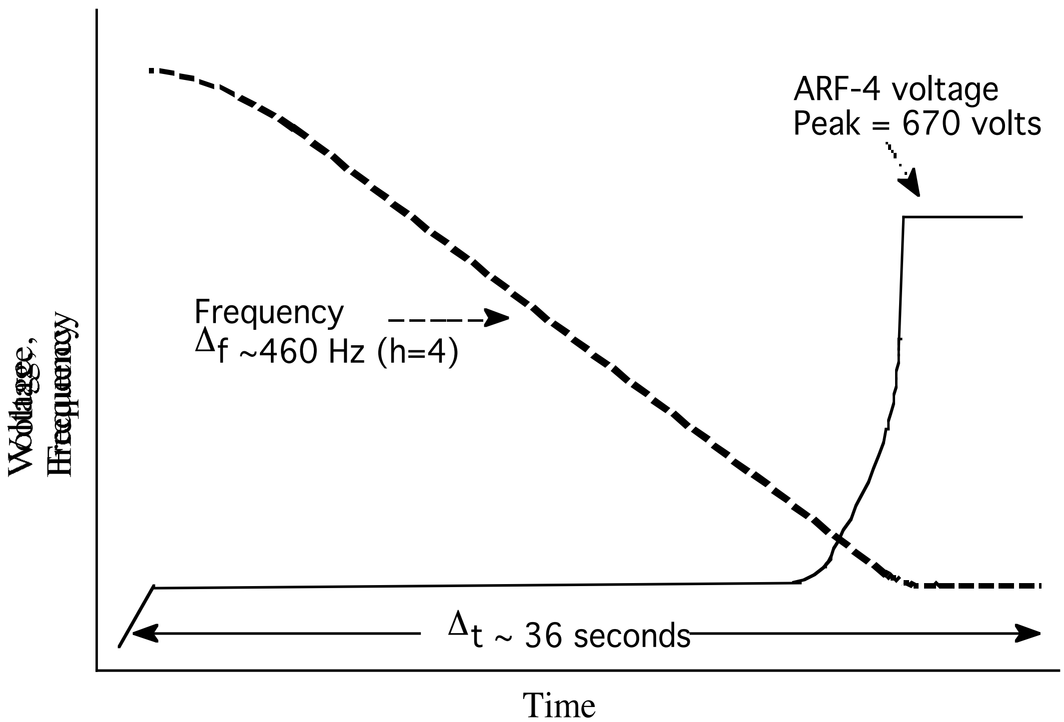

Figure 4.8 ARF-4 waveform for unstacking with a 0.35 eV-s bucket

inputs are provided by a DDS, which can have a DC value (A:R2FSET) or be driven by a 468 card (A:R268FF). At a later date a different 468 card (A:468F) will be used for the frequency waveform.